

To appear in ApJ Letters, scheduled for the issue of September 20, 1996

Discovery of Sub-Millisecond Quasi-Periodic Oscillations in the X-Ray Flux of Scorpius X-1

M. van der Klis

*Astronomical Institute “Anton Pannekoek”, University of Amsterdam
and Center for High-Energy Astrophysics, Amsterdam*

J.H. Swank, W. Zhang, K. Jahoda
Goddard Space Flight Center, NASA

E.H. Morgan, W.H.G. Lewin
Massachusetts Institute of Technology

B. Vaughan
California Institute of Technology
and

J. van Paradijs
University of Alabama at Huntsville and University of Amsterdam

ABSTRACT

We report the discovery, with NASA’s Rossi X-ray Timing Explorer (RXTE), of the first sub-millisecond oscillation found in a celestial X-ray source. The quasi-periodic oscillations (QPO) come from Sco X-1 and have a frequency of approximately 1100 Hz, amplitudes of 0.6–1.2% (rms) and are relatively coherent, with Q up to $\sim 10^2$. The frequency of the QPO increases with accretion rate, rising from 1050 to 1130 Hz when the source moves from top to bottom along the normal branch in the X-ray color-color diagram, and shows a strong, approximately linear correlation with the frequency of the well-known 6–20 Hz normal/flaring branch QPO. We also report the discovery of QPO with a frequency near 800 Hz that occurs, simultaneously with the 1100 Hz QPO, in the upper normal branch. We discuss several possible interpretations, one involving a millisecond X-ray pulsar whose pulses we see reflected off accretion-flow inhomogeneities. Finally, we report the discovery of ~ 45 Hz QPO, most prominent in the middle of the normal branch, which might be magnetospheric beat-frequency QPO.

Subject headings: stars: individual (Sco X-1) — stars: neutron — pulsars: general

1. Introduction

The characteristic time scale for motion of matter near a gravitating object, the dynamical time scale τ_{dyn} , is $(r^3/GM)^{1/2}$, where r is the distance to the object and M its mass. For $r = R$, the size of the object, τ_{dyn} is relevant to possible spin and vibration periods. For a neutron star τ_{dyn} extends down to values of well below 1 ms. Sub-millisecond variability could therefore be produced in an accreting neutron star by various different mechanisms. In this paper, we present the first conclusive evidence for sub-millisecond variability in an accreting neutron star, Sco X-1. A preliminary announcement of this work was already made in Van der Klis et al. (1996).

Sco X-1 (Giacconi et al. 1962), the brightest persistent X-ray source in the sky, is a Z source (Hasinger and Van der Klis 1989), a luminous low-mass X-ray binary containing a low-magnetic-field neutron star. In the X-ray color-color diagram it shows the lower two of the three branches in the canonical “Z track”, the normal branch (NB) and the flaring branch (FB) (Middleditch and Priedhorsky 1986, Priedhorsky et al. 1986, Hertz et al. 1992, Dieters and Van der Klis 1996). Its power spectrum is characterized by the presence of 1–5% amplitude, 6–20 Hz normal/flaring branch QPO (N/FBO). According to the standard interpretation (e.g., Hasinger et al. 1990, Lamb 1991), when the mass transfer rate \dot{M} to the neutron star increases, the source moves down along the NB, passes through the “vertex” of the two branches, where it reaches the Eddington critical rate, and then moves up the FB. At the same time the QPO frequency increases from ~ 6 Hz on the NB to ~ 20 Hz on the lower FB. Further up the FB the QPO disappear. Below, we report three new, previously unknown QPO phenomena in this source, and describe their dependence on \dot{M} .

2. Observations

Sco X-1 was observed three times with the proportional counter array (PCA) onboard NASA’s Rossi X-ray Timing Explorer (RXTE; Bradt, Rothschild and Swank 1993), on 1996 Feb. 14 from 9:14 to 13:25 UT, Feb. 18 4:46–8:40 UT and Feb. 19 10:09–14:56 UT, hereafter observations 1, 2 and 3, respectively. Each observation covered three satellite orbits with ~ 2500 s of data, separated by intervals of ~ 1500 s due to Earth occultation and/or South-Atlantic Anomaly passage. The count rate was $\sim 10^5$ c/s in observations 1 and 2.

At the start of orbit 1 of observation 3 the count rate increased to $\sim 1.45 \cdot 10^5$ c/s, which tripped the PCA high-voltage safety switch-off. RXTE was then moved slightly off Sco X-1 to $\sim 50\%$ collimator efficiency; later count rates were between 0.5 and $0.8 \cdot 10^5$ c/s. The < 20 keV background was $\lesssim 90$ c/s and has been neglected.

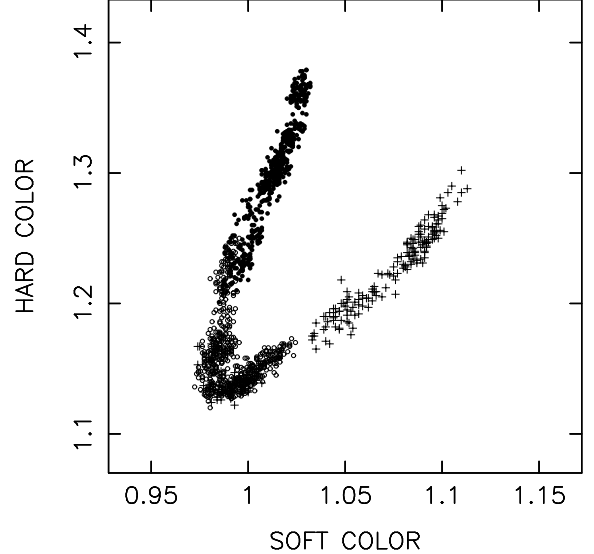


Fig. 1.— X-ray color-color diagram. Soft color is the (3-5)/(1-3) keV, hard color the (7-20)/(5-7) keV count-rate ratio. Each data point corresponds to 16 s of data; filled circles, open circles and crosses correspond to observations 1, 2 and 3, respectively. The statistical uncertainties are ~ 0.003 in soft color and ~ 0.005 in hard color. The systematic uncertainties in Z track location between observations (see text) are $\sim 1\%$.

During orbits 1 and 3 of each observation, data were collected with a time resolution of initially 0.5 ms and later, after discovery of the 1100 Hz QPO in observation 1, usually 0.25 ms. During orbit 2 of each observation, the time resolution was set to $16 \mu\text{s}$, and “double events” were additionally recorded at $64 \mu\text{s}$ time resolution. Double events, two events detected within $6 \mu\text{s}$ at two different anodes of a PCA detector, are normally mostly due to charged particles. However, for the very high count rates from Sco X-1 they are mostly due to two source photons. In the data analysis the double events, counted as two, were added to the single-photon data. This led to a con-

siderable increase in sensitivity to time variability. All high-time-resolution data were recorded in the 2–20 keV band. During the entire run 16-s resolution data were additionally recorded in 129 spectral channels covering the 2–60 keV band.

3. Analysis and Results

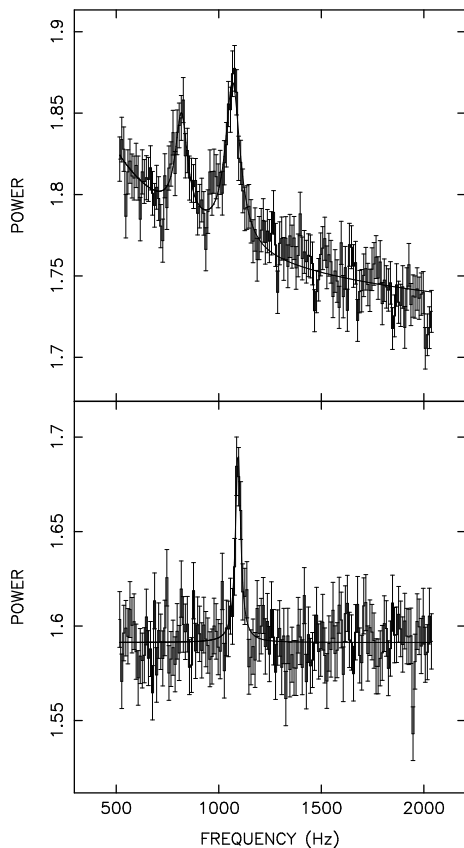


Fig. 2.— Power spectra of combined single- and double-event data (see text) showing simultaneous 800 and 1100 Hz QPO (*top*; orbit 2 of observation 1), and a narrow 1100 Hz QPO peak (*bottom*; orbit 2 of observation 2). The spectra are Leahy-normalized; the offsets of the continua from a level of 2.0 and the slope of the continuum in observation 1 are due to instrumental deadtime effects.

We used the 16-s data to construct X-ray color-color diagrams. There was a considerable offset between the Z track seen in observations 1 and 2 and that in observation 3, which we attribute to

energy-dependent detector effects (collimator reflections and/or rate-dependent gains). After an empirical correction that assumes the Z track did not move between our observations (e.g., Dieters and Van der Klis 1996), a typical Sco X-1 color-color diagram results (Fig. 1). During observation 1 the source moved gradually down the NB, during observation 2 it moved up and down between the lower NB and FB, and in observation 3 it moved gradually down the FB and into the vertex region. We assigned numbers S_Z to positions on the Z track according to curve length along the track, where we set the top of our NB to 1, and the vertex to 2.

Approximately 1100-Hz QPO (Fig. 2) were observed on all occasions that the source was on the NB or very low on the FB, and the observational set-up was adequate (full collimator efficiency to ensure sufficient sensitivity, and sufficient time resolution). This was the case in orbit 2 of observation 1 and in orbits 1 and 2 of observation 2. The QPO were seen independently in single and in double-event data. Table 1 lists the results of functional fits of a constant plus a power law plus one or two Lorentzian peaks to power spectra of the high time resolution data. All fits were statistically acceptable with reduced $\chi^2 \sim 1$. The QPO frequency, ν_{1100} , increased with \dot{M} , from 1050 Hz at $S_Z = 1.25$ to 1130 Hz at $S_Z = 2.1$. Note that for lack of time resolution we have no information about the 1100 Hz QPO in the S_Z range 1.4–1.8. The QPO were sometimes quite coherent, with $Q \equiv \nu/\Delta\nu$ up to 10^2 . Fractional rms amplitudes, corrected for differential deadtime (Van der Klis 1989) assuming a paralyzable process (Zhang et al. 1995) with a dead-time of 10 μ s (Zhang 1995) ranged between 0.9 and 1.2% in observation 1 and 0.6–0.9% in observation 2. There was no clear dependence on \dot{M} within each observation.

QPO with a frequency of approximately 800 Hz were observed simultaneously with the 1100-Hz QPO (Fig. 2 (*top*)) only when the source was in the upper NB ($S_Z < 1.36$). From studying the short-term power-spectral variations we can exclude that the two peaks are due to one peak moving in frequency, unless it moves on time scales shorter than 32 s. In orbit 2 of observation 1 the QPO frequency, ν_{800} , generally increased (from ~ 800 to ~ 830 Hz) when S_Z rose from 1.25 to 1.35 (ν_{1100} increased from 1050 to 1075 Hz over the same range). The 800 Hz QPO were relatively broad, 50 to >100 Hz and had amplitudes between 0.9 and 1.2% (rms), decreasing slightly with S_Z . In

orbit 1 of observation 1 ($S_Z < 1.16$) the sensitivity was less due to the lack of double-event data, but there was some evidence (3σ) for the presence of a broad peak near 720 Hz.

A third new QPO feature, located near 45 Hz, was detected on the NB. These QPO had a FWHM of typically 15–25 Hz, an amplitude of $\sim 1\%$ (rms) and were most prominent on the middle of the NB, near $S_Z = 1.5$. They were detected all the way from $S_Z = 1.1$ to 1.9 with little change in frequency. Fig. 3 shows the power spectrum of data obtained in orbit 3 of observation 1, with 6 Hz QPO (the N/FBO) and 45 Hz QPO.

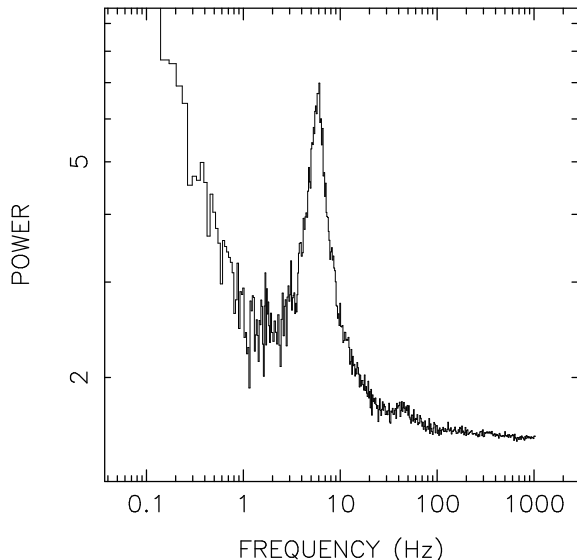


Fig. 3.— Power spectrum of 0.5 ms resolution data obtained in orbit 3 of observation 1, showing a strong N/FBO peak centered on 6 Hz, and a weaker feature near 45 Hz. The spectrum is Leahy-normalized; the offset of the continuum from a level of 2.0 is due to deadtime effects.

The dependencies of ν_{1100} and the N/FBO frequency $\nu_{N/FBO}$ on S_Z are very similar. The relation between ν_{1100} and $\nu_{N/FBO}$ is plotted in Fig. 4. There is a strong correlation. The relation fits a straight line, with $\nu_{1100} = 7.3 \cdot \nu_{N/FBO} + 1032$; a power law fits as well.

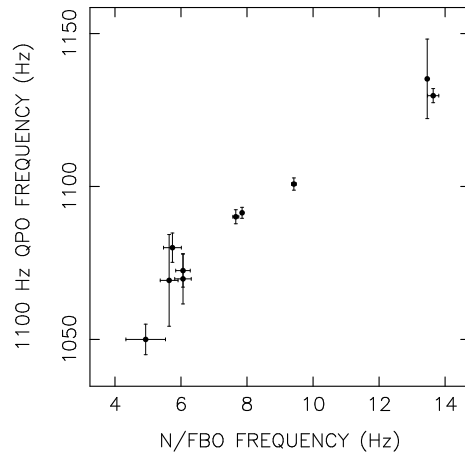


Fig. 4.— Relation between the frequencies of the 1100 Hz QPO and the N/FBO as derived from data where these two phenomena were detected simultaneously. A strong correlation is evident.

4. Discussion

The discovery of near-millisecond (Strohmayer, Zhang and Swank 1996, Van Paradijs et al. 1996, this paper) and submillisecond (Van der Klis et al. 1996, this paper) oscillations from accreting low-magnetic-field neutron stars was expected on the basis of general arguments (see Introduction). To find and study such phenomena was one of the primary objectives of the RXTE mission. There is a range of phenomena that could take place on these time scales, and we shall not attempt to be exhaustive here. The fact that both ν_{1100} and ν_{800} increase considerably as a function of \dot{M} suggests an origin in accretion phenomena rather than neutron star vibrations (e.g., McDermott, Van Horn and Hansen, 1988). Therefore, we concentrate on that class of models.

Disk frequency. The Kepler frequency ν_K at the inner edge of the accretion disk, bounded by a small (16–20 km) magnetosphere is in the correct range to be identified with either ν_{1100} or ν_{800} . It would increase with \dot{M} , as observed. The \dot{M} dependence of the 800 Hz QPO, strongest at low \dot{M} and disappearing towards higher \dot{M} is reminiscent of the “horizontal branch QPO” (HBO) in other Z sources (Van der Klis et al. 1985, Van der Klis 1995 for a review). These HBO, in the beat-frequency model (Alpar and Shaham 1985, Lamb et al. 1985), are caused by “clumps”

in the inner disk, which are most prominent at the lowest \dot{M} levels. The 800 Hz QPO (or, alternatively, the 1100 Hz QPO) could be a direct signal from these clumps, either by reflection or obscuration of the X-ray flux from the central regions, or by interaction with azimuthal structure in the radial flow (see below).

Beat frequency. As no HBO have been detected as yet from Sco X-1, an alternative possibility is that the 800 Hz QPO are HBO, and their frequency the beat frequency $\nu_B = n(\nu_K - \nu_s)$ between ν_K and the neutron star spin frequency ν_s , where n is the field symmetry factor. This would make the HBO in Sco X-1 *much* faster than those in other Z sources, whose frequency is 15–55 Hz, and would require a relatively slow neutron star spin rate (not more than a few 100 Hz). When this Letter was about to be submitted, the detection was reported in 4U 1728–34 of 363 Hz oscillations during X-ray bursts (Strohmayer et al. 1996) which were interpreted as due to the neutron star spin, and two variable-frequency QPO peaks (one of which the ~ 800 Hz QPO reported by Strohmayer, Zhang and Swank, 1996) whose separation remained near 363 Hz. Clearly, this suggests a beat frequency model interpretation with ν_B , ν_K and ν_s all visible. In the case of Sco X-1, the difference $\nu_{1100} - \nu_{800}$ is consistent with being constant near 250 Hz, but the range in frequencies over which both peaks are detected simultaneously is too small to draw any strong conclusion from this; there is no evidence for an oscillation near 250 Hz.

The new 45 Hz QPO in Sco X-1 are in the range of HBO frequencies seen in the other Z sources. The dependence of their amplitude on S_Z is clearly different from that of HBO in GX 5–1 and Cyg X-2, which are strongest at the top of the NB (and in the HB), not in the middle of the NB. In GX 17+2, 60 Hz QPO have been discovered in the NB which may be a similar phenomenon (Wijnands et al. 1996, in prep.). If the 45 Hz QPO in Sco X-1 are beat-frequency QPO, then from the fact that its frequency is approximately constant we conclude that the 1100 Hz and the 800 Hz QPO, whose frequencies vary by tens of Hz, can not be the disk frequency.

Doppler-shifted pulsar. The strong correlation we observe between ν_{1100} and $\nu_{N/FBO}$ is not explained by any of the models discussed above. It could in principle arise because both frequencies vary as a function of \dot{M} independently of each other, but this seems unlikely. The $\nu_{N/FBO}$ vs. S_Z relation is known to jump at

$S_Z=2$ (see, e.g., Van der Klis 1995), and ν_{1100} should then, independently, show a similar jump in its dependence on S_Z to maintain the correlation. It seems more likely that one frequency is by some mechanism directly derived from the other one.

We briefly explore a mechanism where this is the case. In the Fortner, Lamb and Miller (1989) model for N/FBO, part of the accretion takes place by way of an approximately radial inflow, and blobs (inhomogeneities) in this flow produce the N/FBO. For a constant-size radial flow, $\nu_{N/FBO}$ is proportional to the inflow velocity v_r . If the 1100 Hz QPO are the Doppler-shifted pulsar signal, which we see reflected off blobs in the flow, then when v_r varies, ν_{1100} would vary linearly with $\nu_{N/FBO}$, as observed. For a blob moving towards the star along a radius vector that makes an angle ϕ with the line of sight, ν_{1100} would be proportional to $(1 + (1 - \cos \phi)v_r/c)\nu_{puls}$, where ν_{puls} is the pulse frequency. Radial flow velocities up to at least $0.04c$, and spin frequencies of ~ 500 or ~ 1000 Hz, depending on whether one or two magnetic poles contribute to the signal, are required for this model to work. To get the relatively coherent QPO signal we observe, the range of angles ϕ contributing to the signal should be small. This would be true, for example, if the magnetic and rotation axes are nearly aligned. Aligned rotation would also explain why millisecond pulsars in low-mass X-ray binaries have been hard to find. This model would require a spin period ~ 1 ms, faster than any neutron star spin yet measured, as only one pole would contribute (the other pole could produce another QPO peak).

Note. Further RXTE observations of Sco X-1 on May 24-25 again show the two high-frequency QPO peaks, this time with frequencies near 900 and 600 Hz. Their separation is significantly ($>10\sigma$) larger than in the February observations. This excludes the beat-frequency interpretation where the peak separation is predicted to be constant at the neutron star spin frequency.

This work was supported in part by the Netherlands Organization for Scientific Research (NWO) under grant PGS 78-277 and by the Netherlands Foundation for Research in Astronomy (ASTRON) under grant 781-76-017. WHGL and JVP acknowledge support from the National Aeronautics and Space Administration.

REFERENCES

- Alpar, M.A., Shaham, J. 1985, *Nature*, 316, 239.
- Bradt, H.V., Rothschild, R.E., Swank, J.H. 1993, *A&AS*, 97, 355.
- Dieters, S., Van der Klis, M. 1996, *A&A*, submitted.
- Fortner, B.F. 1993, PhD Thesis, Univ. of Illinois at Urbana-Champaign.
- Giacconi, R., Gursky, H., Paolini, F., Rossi, B. 1962, *Phys. Rev. Lett.*, 9, 439.
- Hasinger, G., Van der Klis, M. 1989, *A&A*, 225, 79.
- Hasinger, G., Van der Klis, M., Ebisawa, K., Dotani, T., Mitsuda, K., 1990, *A&A*, 235, 131.
- Hertz, P., Vaughan, B., Wood, K.S., Norris, J.P., Mitsuda, K., Michelson, P.F., Dotani, T. 1992, *ApJ*, 396, 201.
- Lamb, F.K., 1991, in: *Neutron Stars: Theory and Observation*, NATO ASI C344, p. 445.
- Lamb, F.K., Shibazaki, N., Alpar, M.A., Shaham, J. 1985, *Nature*, 317, 681.
- McDermott, P.N., Van Horn, H.M., Hansen, C.J. 1988, *ApJ*, 325, 725.
- Middleditch, J., Priedhorsky, W.C., 1986, *ApJ*, 306, 230.
- Priedhorsky, W.C., Hasinger, G., Lewin, W.H.G., Middleditch, J., Parmar, A. Stella, L., White, N., 1986, *ApJ*, 306, L91.
- Strohmayer, T., Zhang, W., Swank, J. 1996, *IAU Circ.*, 6320.
- Strohmayer, T., Zhang, W., Smale, A., Day, C., Swank, J., Titarchuk, L., Lee, U., 1996, *IAU Circ.*, 6387.
- Van der Klis, M. 1989, NATO ASI C262: *Timing Neutron Stars*, Ögelman and van den Heuvel (eds.), Kluwer, p. 27.
- Van der Klis, M. 1995, in: *X-Ray Binaries*, Lewin, Van Paradijs and Van den Heuvel (eds.), Cambridge University Press, p. 252.
- Van der Klis, M., Jansen, F., Van Paradijs, J., Lewin, W.H.G., van den Heuvel, E.P.J., Trümper, J.E., Sztajno, M. 1985, *Nature*, 316, 225.
- Van der Klis, M., Swank, J., Zhang, W., Jahoda, K., Morgan, E., Lewin, W., Vaughan, B., Van Paradijs, J. 1996, *IAU Circ.*, 6319.
- Van Paradijs, J., Zhang, W., Marshall, F., Swank, J.H., Augusteijn, T., Kuulkers, E., Lewin, W.H.G., Lamb, F., Lapidus, I., Lochner, J., Strohmayer, T., Van der Klis, M., Vaughan, B. 1996, *IAU Circ.*, 6336.
- Zhang, W., Jahoda, K., Swank, J.H., Morgan, E.H., Giles, A.B. 1995, *ApJ*, 449, 930.
- Zhang, W. 1995, XTE/PCA Internal Memo.

TABLE 1
QPO PARAMETERS

S_Z	1100 Hz		800 Hz		N/FBO	
	Frequency (Hz)	FWHM (Hz)	Frequency (Hz)	FWHM (Hz)	Frequency (Hz)	FWHM (Hz)
Observation 1 orbit 2.						
1.252±0.027	1050.3±1.1	41±5	803±3	88±11	4.9±0.6	13±3
1.282±0.040	1069.8±8.2	104±30	794±20	145 ⁺¹⁸⁹ ₋₅₀	6.06±0.25	9.3±1.1
1.336±0.032	1080.0±4.8	50±19	833±12	80 fix	5.74±0.28	10.7±1.1
1.340±0.050	1072.5±5.4	78±18	829±5	49±19	6.06±0.22	8.5±0.8
1.357±0.022	1069±15	178 ⁺¹⁴⁹ ₋₆₅	820±12	80 fix	5.64±0.27	9.9±1.1
Observation 2 orbit 2.						
1.866±0.022	1091.4±1.8	22±5	—	—	7.85±0.04	4.44±0.12
1.929±0.050	1100.8±2.0	18±4	—	—	9.42±0.07	7.24±0.23
Observation 2 orbit 1.						
1.966±0.032	1090.1±2.3	18±6	—	—	7.66±0.09	5.81±0.27
2.057±0.006	1129.7±2.3	13.4 ^{+6.2} _{-1.4}	—	—	13.64±0.17	6.6±0.6
2.092±0.025	1135±13	68 ⁺⁸⁸ ₋₄₀	—	—	13.46±0.04	9.60±0.18

Fit function: see text. All errors correspond to unreduced $\Delta\chi^2 = 1$. Fit range, frequency resolution and number of degrees of freedom for the 1100 and 800 Hz QPO fits were 200–2000 Hz, 10 Hz and 171 for observation 1 orbit 2, 512–1536 Hz, 5 Hz and 200 for observation 2 orbit 1 and 200–2000 Hz, 5 Hz and 356 for observation 2 orbit 2, respectively.